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Observations of an Intense Anticyclonic Warm Eddy in the Newfoundland Basin

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Abstract.
An intense anticyclonic warm eddy was sampled in February 1997 in the Newfoundland Basin. Its presence, detected during a hydrographic survey, was further corroborated through ERS/TOPEX sea surface height anomaly and satellite tracked drifters. This 120 km wide eddy was very homogeneous in temperature and salinity down to 800 m and its transport (15-1800 dbar) reached 27 Sv. Its location, 49°N 40°W, in the warm and saline waters of the Northwest Corner, the northernmost position reached by the North Atlantic Current, is clearly exceptional. Although intense anticyclonic eddies have previously been observed with satellite tracked buoys and RAFOS floats, this is the first eddy (to our knowledge) ever documented at such a high latitude in the North Atlantic Current system. Its formation is discussed in term of thermohaline processes.

Introduction

The North Atlantic Current (NAC) is known as the northward branch derived from the Gulf Stream, downstream from the Newfoundland Rise [*Rossby*, 1996]. Its northward trajectory follows the continental slope along the Grand Banks. Near 51°N, the NAC turns eastward in a structure called the Northwest Corner (NWC), and then flows broader and more diffuse towards the Mid-Atlantic Ridge. Along the Grand Banks, the NAC appears strongly locked to bathymetry [*Kearns and Rossby*, 1998] and developp several meanders, which favor the formation of recirculation areas and eddies. One of them, the Mann eddy is an intense, warm center anticyclonic eddy northeast of the branching point of the Gulf Stream into the NAC and the Azores Current, near 41°N 43°W. [*Lazier*, 1994] reported the presence of two anticyclonic 100 km wide eddies in the NWC, in which drifters drogued at 100 m moved with peak velocities up to 1 ms^{-1}. [*Prater and Rossby*, 1999] discussed the possible subduction and movement of one eddy observed at 49°N 41°W by an isopycnal RAFOS float. However, the deep internal structure of these eddies has never been observed until now. In this paper, we describe an intense anticyclonic warm eddy which was crossed in February 1997 near 49°N 40°W. To our knowledge, this is the best sampled eddy embedded in the NAC system at such a high latitude.

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The experiment, data and mapping

The Couplage avec l'Atmosphère en Conditions Hivernales (CATCH) experiment [*Eymard et al.*, 1999] was part of the Fronts and Atlantic Storm Tracks EXperiment (FASTEX, [*Joly et al.*, 1999]). It took place in January - February 1997 in the Newfoundland Basin, on board the *R/V Le Suroît*. One of its objectives was to document the various jets associated with the NAC branching. The survey consisted of four sections with Conductivity Temperature Depth (CTD) profiles between 0 and 2000 m, every 10 to 20 nautical miles. The sections constitute a trapezoidal survey (Figure 1) designed to span the Labrador Current, the NWC and the branches of the NAC. The northern section (with 24 CTDs) was covered from February 11th to 25th, during which an intense eddy was encountered. The ship, equipped with a thermosalinograph and an Acoustic Doppler Current Profiler (ADCP), enabled continuous measurements of Sea Surface Temperature (SST), salinity and currents (0-150 m). Baroclinic mass transports were computed from pairs of CTD casts. WOCE SVP 15 m depth drogued and satellite tracked drifters were launched by the *R/V Le Suroît* and the American ship *R/V Knorr*. Drifter locations were provided by the Argos satellite tracking system, with a rate of 16 positions per day. The positions of drifters were interpolated every hour, after which their velocities were computed. Specific analyses of SST and of Sea Level Anomalies (SLA) from TOPEX/POSEIDON were pro-

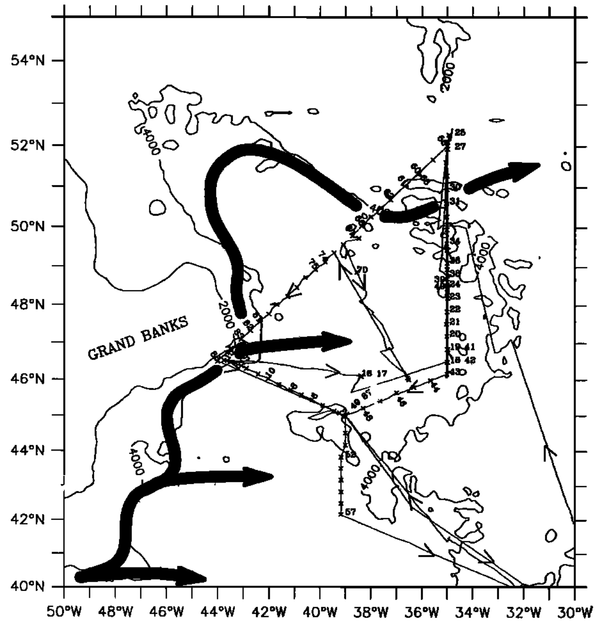

Figure 1. Ship track during the CATCH experiment: the arrows indicate the direction along the track and crosses the CTD stations with corresponding number. A schematic of the NAC system is represented from *Kearns and Rossby* [2001].

duced and time centered on February 23rd [*Caniaux et al.*, 2001]. Because SLA are obtained by removing the mean sea level, a background dynamic height anomaly, derived from a seasonal winter climatology [*Kearns and Rossby*, 2001], has been added.

Results

Along the northernmost leg, one CTD station (station 75) had an exceptional mixed layer depth. This cast contained isothermal (12,97° C) and isohaline (35.89 psu) ($\sigma_\theta = 27.09$ kg m^{-3}) water down to 800 m (Figure 2). Two casts (74 and 76) presented deep mixed layers but only of 550 m and 700 m depth respectively. These profiles were warmer and saltier than the surrounding water down to 1000 m. The $\theta - S$ diagram indicates the presence of "pure" North Atlantic Central Water [*Arhan*, 1990] modified by cooling at the surface, meaning that the origin of this water is certainly from the Gulf Stream. The ADCP measured south-easterly currents up to 1 ms^{-1} and northerly currents up to 0.75 ms^{-1} respectively to the northeast and southwest of station 75 (Figure 3). These data thus indicated that an anticyclonic, warm center eddy or ridge had been met. Transports (15-1800 dbar) calculated from contiguous CTD casts (Figure 3) were 25.8 Sv and 27.3 Sv (1 Sv = 10^6 m^{3}s^{-1}) respectively between stations 73 and 75 and stations 75 and 77. If the NAC can be delimited by the isotherms 9° C and 10° C (the strongest SST gradient), then the NWC was centered near 50°N 42°W during the experiment (Figure 4). From the SST analysis, the three CTD casts lie outside the front limiting the NWC: the eddy (or ridge) was thus detached from the NAC and embedded in the warm waters of the NWC. The SLA chart reveals the presence of a 120 km wide eddy centered at 48°15′N 39°45′W, in close agreement with the location of the three CTD casts. Both satellite altimetry and dynamic height calculations from the CTD data confirm that the SLA was 20 cm higher within the eddy compared to outside. Currents derived from altimetry (Figure 4) reached a peak value of 0.6 ms^{-1} on the northwestern rim of the eddy. Note that the eddy center derived from altimetry is located on the southeastern side of the ship trajectory, meaning that the eddy center was not reached during the cruise and that the mixed layer could still have been deeper there than observed. Three SVP drifters were trapped in the eddy at the end of February (Figure 4). The location of the eddy deduced from the drifter trajectories matches quite well the one deduced from altimetry. The drifters turned at least once around the eddy center with an orbital period of 6 to 9 days. Two of them left the eddy on its southeastern side. Drifter velocities varied from 0.1 ms^{-1} to 1.4 ms^{-1} with a mean of 0.6 ms^{-1}. We thus deduce that the mean eddy diameter was 120 km.

Finally we conclude that the combination of CTD, ADCP, altimetry and drifter data confirms the existence of a 120 km wide, intense anticyclonic eddy, embedded in the warm and saline water inside the NWC, at 49°N 40°W. Its extremely well mixed layer was sampled down to 800 m but it is likely that the mixed layer in the center of the eddy was even deeper.

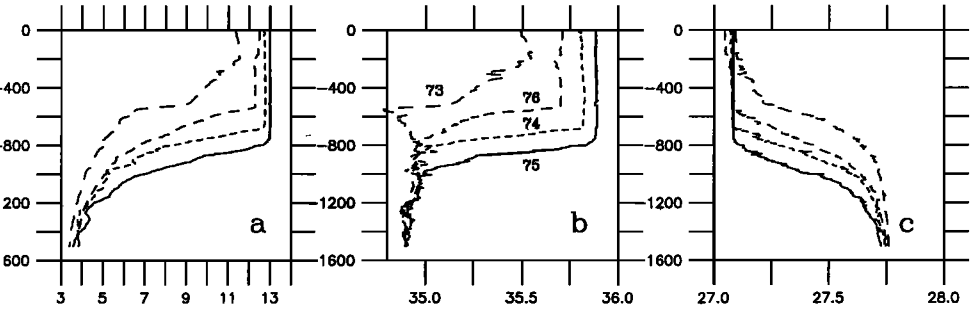

Figure 2. (a) Temperature (° C), (b) salinity (psu) and (c) potential density (kg m^{-3}) versus depth (m) collected at CTD station 73, 74, 75 and 76.

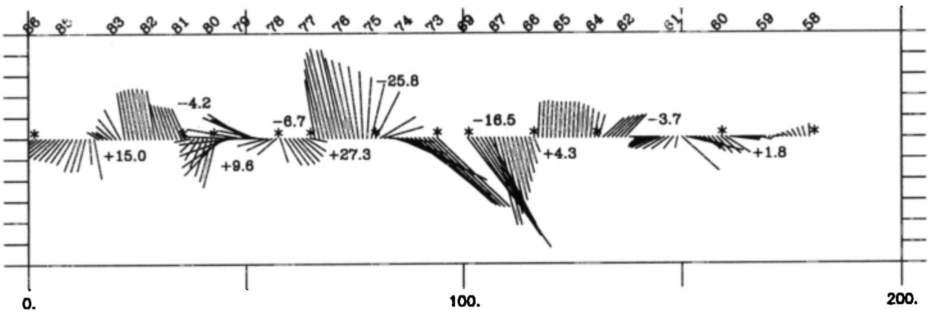

Figure 3. ADCP currents in ms^{-1} (subsampled every 5 km) and mass transport (15-1800 dbar) in Sv from west (left) to east (right), along the ship trajectory. The transports were calculated from pair of CTD stations, the location of which is indicated by stars. A positive (negative) sign means a northwestward (southeastward) transport relative to the NE-SW ship trajectory.

Formation

The sampled eddy (referred as the NWC eddy [*Prater and Rossby,* 1999]) shares several similarities with the Mann eddy: warm anticyclonic eddy embedded in the warm, salty waters of the NAC, great depth of the thermocline, huge heat and salt contents, deep deflection of the isopycnals, etc... The origin of the Mann eddy was discussed by [*Rossby,* 1996] and its presence results from the very particular circulation of the NAC in this area. Rossby notes that between the Newfoundland ridge and the NWC, the NAC makes quasi-permanent non propagating meanders. [*Kearns and Paldor,* 2000] showed that these meanders have no unstable modes and that their wavelength is strictly determined by the bathymetry. So, when the NAC approaches one of the permanent cyclonic troughs, the water parcels cannot adjust to the strong change of vorticity and they are ejected from the current, recirculate and form an anticyclonic eddy on the right side of the jet. Consequently we infer that: 1. the formation of these eddies is essentially dynamic and related to how the flow is locked to the bathymetry; 2. they directly pick up their vorticity, heat and salt from the NAC; 3. they form in the vicinity of their zone of residence, where the NAC starts a marked cyclonic curve.

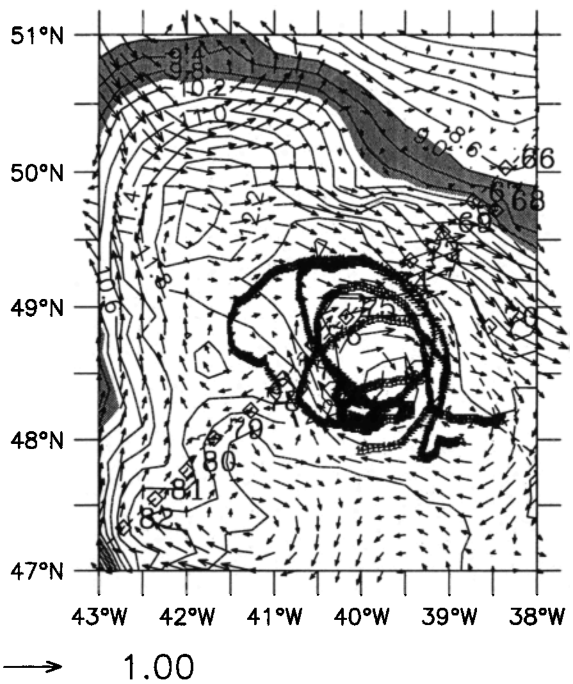

Figure 4. Synoptic SST analysis (contour interval 0.4° C) centered on 1997/02/23. Waters between 9° C and 10° C are shaded. Superimposed, the current field deduced from satellite. Dashed line indicates the ship trajectory, with the position of the numbered CTD stations indicated by diamonds. The trajectories of three SVP drifters (symbols 1, 2 and 3 respectively for buoy number 44601, 44602 and 44603) cover a period of 15 days centered on 1997/02/23. Open circles mark the beginning of the trajectories.

Which are the physical processes that form so deep, warm and well mixed layers? Horizontal advection of negative vorticity generates downward vertical velocities in the eddy as indicated by the quasi-geostrophic theory [*Holton,* 1979]:

$$\frac{\partial w}{\partial z} = \frac{\vec{V}.\vec{\nabla}(\zeta + f)}{\zeta + f} \tag{1}$$

$\zeta + f$ is the absolute vorticity, sum of the relative vorticity ζ and Coriolis parameter f; $\vec{V}$ is the velocity of the horizontal current and w the vertical velocity. Equation (1) means that if the advection term $\vec{V}.\vec{\nabla}(\zeta + f)$ is positive (which happens when the water parcels ejected from the NAC transfer their negative vorticity to the eddy), then the vertical shear of w is positive (the absolute vorticity $\zeta + f$ is always positive) and w increases with depth. Increasing w favors convergence inside the eddy through mass conservation. Our data suggest that horizontal advection occurs in the top 300 m, since below this depth the water inside the eddy is warmer and saltier than outside. Heat and salt are then transferred downwards through convection and advection, as enabled by downward vertical velocities.

How do surface fluxes affect the eddy properties? An evaluation of the surface heat budget was performed for January and February 1997 at a scale of 18 km to take into account the heterogeneities of the SST field.

The heat budget was calculated: 1. from satellite fields for the radiative fluxes, 2. from European Centre for Medium-Range Weather Forecasts (ECMWF) model atmospheric fields and 3. from a bulk parameterization [*Eymard et al.*, 1999] for the turbulent fluxes. This estimate indicates that the NWC is an area of strong heat flux anomaly in winter, i.e. significantly higher than the climatology of [*Isemer and Hasse,* 1987]. In February, the net heat loss was considerable, reaching a peak value of 650 Wm^{-2} and less than 300 Wm^{-2} on the cold waters inshore of the NAC. This anomaly is due to the frequent passage of the cold sectors of atmospheric waves [*Giordani and Caniaux,* 2001]. Surface fluxes lower the heat content in the eddy and their effect is opposed to the warming of the 300 m top layers. They favor convection, reinforce the downward vertical velocities in the top layers and add to horizontal advection through mass conservation.

Conclusion

The formation processes of the warm eddies present along the warm side of the NAC in the Newfoundland Basin, lead us to conclude: 1. as these eddies are fed by horizontal advection of heat, salt and vorticity directly from the NAC and as the NAC gradually loses heat and energy along its path northwards, the NWC eddy tends to be less warm, deep and energetic than the Mann eddy; this result is directly confirmed by our observations; 2. the fact that surface fluxes are much stronger in the NWC than elsewhere in winter, and that their bulk effect is opposed to the upper level heating by horizontal advection, the NWC eddies are probably slower to form than the Mann eddy; 3. we suggest that the NWC eddies need a period long enough to develop significant mixed layer depth. The strong turbulence that reigns in the Newfoundland Basin can easily perturb the flow and prevent the permanency necessary for its deepening. These conclusions suggest that the NWC eddies are less permanent and frequently observed than the Mann eddy.

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